GRAVITY SURVEY OF THE MT. TOONDINA IMPACT STRUCTURE SOUTH AUSTRALIA

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ABSTRACT

Gravity and seismic reflection data, together with geologic **mapping,** indicate that the Mount Toondina feature in South Australia is best interpreted as an eroded 4-km-diameter impact structure consisting of a ring structural depression surrounding a pronounced central uplift. Beds at the center of the structure within the central uplift have been raised as much as 200 m from depth and deformed by convergent flow. Seismic reflection data indicate that deformation extends to depths of only -800 m; at greater depths the reflectors are nearly flat lying indicating little or deformation. Gravity data show residual anomalies of +1.0 mGal coincident with the central uplift and a -0.5 regal low associated with the ring structural depression. Modeling of the gravity data indicates that relatively high-density material occurs within the central uplift, whereas the ring depression is filled with low-density material. The deformation at Mt. Toondina is typical of a complex impact crater; the 4-km diameter is consistent with the expected threshold size for complex craters formed in weak to moderate strength sedimentary rocks.

INTRODUCTION

The Mt. Toondina feature *[Shoemaker and Shoemaker, 1990] is* located in 'northern South Australia, -45 km south of the town of Oodnadatta, and centered at 27° 57' S, 135° 22' E (Figure 1). The structure (Figure 2) is characterized by a core of intensely folded and faulted rocks. Geologic data in combination with geophysical data leads to an interpretation that the Mt. Toondina feature is an impact crater, These data further suggest that the entire Mt. Toondina structure has a diameter of about four kilometers. The original crater topography has been eroded away and the minor topographic promontory of "Mt. Toondina" is formed by travertine spring deposits of *Pleistocene or* possibly late Tertiary age that cap the uplifted and contorted rocks of the central uplift. The age of the impact is estimated to be <110 Ma. The ring structural depression is concealed beneath a thin veneer of Quaternary surficial deposits and characterized by a thickened sequence of strata.

In an attempt to better define the diameter and structural details of the Mt. Toondina structure, geologic mapping and a gravity survey of the area were conducted. Here, we present the results of the gravity survey and seismic reflection data and conclude that the Mt. Toondina structure is of impact origin.

GEOLOGIC BACKGROUND

The Mt. Toondina structure was originally recognized as a structural anomaly from exposures of folded and faulted Permian, Jurassic, and Cretaceus rocks surrounded by a broad expanse of nearly flat-lying beds of the Bulldog Shale of Early Cretaceus age. The feature occurs in the Arckaringa Sub-basin of the Great Artesian Basin of east-central Australia. The Mt. Toondina structure was first mapped by *Freytag* [1964, 1965] who discovered and described the Lower Permian Mt. Toondina Formation and prepared a sketch map of the exposed rocks of the central uplift. He also recognized exposures of the Algebuckina Sandstone of Jurassic (?) age and fine sandstone and shale now assigned to the Cadna-owie Formation of Early Cretaceous age that are locally exposed on the flanks of the central uplift. The Algebuckina Sandstone, a regional aquifer, generates numerous springs from the exposed sandstone; travertine spring deposits cap and conceal many parts of the uplift (Figure 2).

Freytag [1964, 1965] interpreted the structure and the displacement of beds in the center largely in terms of a network of faults. Unpublished detailed geologic mapping by E, M. Shoemaker and D. J. Roddy in 1988 and 1989, however, has shown that the central core is flanked by steeply plunging folds. The Mt. Toondina Formation, in the center of the structure, consists of a sequence of steeply-dipping units that are contorted into a series of tight folds and nappes. The type section of the Mt. Toondina Formation, in fact, is overturned and was erroneously described in inverted stratigraphic order by *Freytag.*

On the basis of geologic and geophysical data, Freytag concluded that the Mt. Toondina structure was a piercement formed by a more or less cylindrical plug -1.5 km wide of Middle or Late Tertiary age penetrating Mesozoic units. Although alluding to an origin as a salt dome, the nature of the piercement was not specified. *Youles* [1976], in a brief note, suggested the Mt. Toondina structure was of impact origin. He based his interpretation chiefly upon similarities between the Mt. Toondina structure and the Gosses Bluff impact structure in Northern Territory *[Milton et al., 1972; Barlow, 1979]. Wopfner [1977]* immediately challenged this interpretation and argued for an origin of the structure as a salt diapir, a conclusion also recently favored by *Jones [1988].*

Extensive seismic exploration of the Arckaringa basin has shown that salt is present in the late Precambrian (Adelaidean) stratigraphic section and that numerous salt diapirs do occur in the subsurface. However, the diapirs are all pre-Permian in age. Moreover, a seismic profile directly across the Mt. Toondina structure (discussed below) shows unequivocally that a salt diapir is not present at depth at Mt. Toondina. The strong shallow deformation at Mt. Toondina dies out with depth; strata are nearly flat lying at depths below -800 m, the base of the Permian Stuart Range Formation. The subsurface structure is consistent with that expected for an impact structure but not with a salt diapir. Thus, the rocks exposed in the center of the structure are interpreted to be an expression of the central uplift.

GRAVITY SURVEY

Data Acquisition

An initial gravity survey of the Mt. Toondina structure was conducted in 1963, Those data were collected, reduced, and interpreted by J, Hall and the results reported in *Freytag* [1964, 1965]. That survey collected measurements along three northeast lines (N64°E) and three northwest lines (N26°W) forming a rectangular grid centered at Mt. Toondina; measurements were made at intervals of 500 feet (152.4 m). Those data indicated a positive residual anomaly of --1.5 mGal centered over Mt. Toondina. The anomaly is attributed by *Freytag* and by *Jones* [1988] to a positive density contrast between Permian sediments exposed within the central uplift and surrounding low-density Cretaceus shales.

To develop a more detailed understanding of the gravity field over the Mt. Toondina feature and determine its extent and structure, additional gravity data were collected by us. Stations were spaced at intervals of 100 m along a two orthogonal lines across the structure (oriented N5°W and N85°E) extending a distance of -4 km from the center, and along a line running obliquely (N28°E) across the feature. The N85°E and N28°E lines coincide with seismic reflection lines run by Dehi Petroleum Pty. Ltd. (discussed below). In addition to data acquired along the lines, numerous gravity measurements 'were made on and around the central uplift. Figure 3a illustrates the location of the gravity stations used in this analyses and includes the new data as well as some of the 1963 data. The 1963 data *were* provided to us by the South Australia Department Mines and Energy in the form of station locations and Bouguer gravity values (reduced using a density of 1.9 g cm-3). The two data sets were merged for this analysis using redundant site measurements. All data were reduced using a density of 1.9 g cm^{-3}, a value representative of the bulk density of the Bulldog Shale, the upper most major stratigraphic unit *in* the region (see below, Figure 6).

Gravity data were collected during this survey using a Worden gravity meter (Master Model HI, No. 758; Meter Constant 0.0877 mGal / dial division). All gravity values *were* tied to a base station on the central uplift, Base station measurements were made every 2 to 3 hours to calibrate meter drift; closure typically was within 1.2 dial divisions (0.09 mGal) and meter drift was typically of the order 0.30 dial divisions per hour (0.02 mGal hr^{-1}). Data were reduced using the USGS Bouguer Gravity Reduction Program; no terrain corrections were made because of the lack of significant near-station topography. Station positions (x, y, z coordinates) were determined using a Leitz SET 4 Electronic Distance Measuring unit. Location and elevation control were tied to the cairn at Mt. Toondina which has a reported elevation of 382 m [*Freytag*, 1965]. No additional benchmarks occur within the survey area to provide elevation or position control.

Data Analysis

Regional gravity in the area surrounding Mt. Toondina is marked by numerous positive and negative anomalies and significant gravity gradients. These variations are attributed to the density contrast between the low-density Mesozoic and Permian sediments and the high-density crystalline basement rocks and sediments of Cambrian-Devonian age [*Milton, 1969; Milton and Morony*, 1976], The most pronounced of the density contrasts is between the high-density Devonian dolomites and the younger low-density sediments. Seismic reflection data in the region indicate significant variations in the thickness of the sedimentary section and the presence of numerous faults; the thickness of the sedimentary rocks overlying pre-Permian strata varies by more than a kilometer within the region.

Figure 3a illustrates the Bouguer gravity within 4 km of Mt. Toondina. Data extend over a 8 km x 8 km square centered on the central uplift. These data were gridded with a 50 x 50 element grid (grid point spacing 320 m) and contoured with a contour interval of 0.5 mGal (a value chosen for clarity of presentation rather than due to limitations in the data). Bouguer gravity values at Mt. Toondina are -17.5 mGal within a regional field that decreases to the northwest at -1.5 mGal km^{-1}. Despite the relatively large gradients, the presence of a residual positive anomaly (~1 mGal) at the central uplift is suggested by a deflection of the contours (Figure 3a). The Bouguer gravity field is also displayed in an oblique 3-D view in Figure 3b; the northwest regional gradient and the high at Mt. Toondina are clearly discernible in this representation.

Due to the regional gravity gradient, details of the gravity field associated specifically with the Mt. Toondina structure are difficult to resolve. In order to isolate the small scale aspects, the regional trend of the gravity data was removed by subtracting a polynomial surface from the data and contouring the residuals. A third-order polynomial was chosen as the best approximation of the regional data such that the mean residual anomaly is approximately zero across the grid; the third-order polynomial accounts for ~97% of the total variation within the data. An oblique 3D view of this residual field is illustrated in Figure 4b. Seismic reflection data indicate a thickening of the Permian and younger sediments to the northwest [*Wopfner*, 1964]. This thickening section of lower density sediments (vis-a-vis the basement) results in a northwest decrease in the regional Bouguer gravity, consistent with the regional field that was removed. Residual gravity values were then gridded and contoured. A grid having 50 x 50 elements with 100 m element spacing extending 2.5 km from the central uplift was used to produce the contour map (Figure 4a).

As can be seen in the residual gravity (Figures 4 a, b), the central uplift is characterized by a well-defined positive anomaly and surrounded by a series of closed-contour lows. The lows completely surround the central uplift, but are of variable amplitude. In part, some of the amplitude variation may be an artifact of uneven station distribution; however, variation is observed even where station control is good. Thus, the variations probably reflect thickness differences of the low-density Bulldog Shale.

The dominant residual gravity feature is the positive anomaly. This high reaches a maximum amplitude of 1.0 mGal above the *general* regional level, and -1.5 mGal above the lowest areas of the annular low, Outside the low, the residual gravity values return to approximately O mGal. The high is --1.25 km in diameter at the O mGal contour and symmetric. The margins are marked by steep gradients (-2.4 $mGal\,km^{-1}$); whereas the center exhibits much lower gradients (-1 regal km^{-1}). The differences in gradient across the anomaly indicate that the source is shallow and steep-sided. The surrounding low typically reaches levels of -0.3 mGal and has a minimum value of - -0.5 mGal in the southeast.

Most simple, bowl-shaped craters, are characterized by a negative gravity anomaly [*Innes*, 1961, 1964; *Pilkington and Grieve, 1992]*. Such negative anomalies can result from several processes. Examples of gravity lows due to a lens of impact breccia and infilling by low-density sediments include Wolf Creek Crater in Australia [*Fudali, 1978]* and Tenoumer in Mauritania [*Fudali and' Cassidy, 1972]*. An example of a gravity low resulting from the impact breccia formed in the crater bottom is Meteor Crater Arizona [*Regan and Hinze, 1975]*. Shattering and fracturing of the original rocks and the formation of impact breccia at the bottom of a crater creates a region of relatively low density producing a negative residual gravity anomaly centered over the crater.

The shape of the gravity anomaly at Mt. Toondina is typical of that of a complex impact crater, i.e., one which has a central uplift. Complex craters display a more complicated gravity signature due the presence of a central uplift. Typically central uplifts are composed of relatively high density material brought up from depth (particularly in craters >30 km diameter and significantly eroded). This high density material, in contrast to the surrounding lower density material, results in a positive gravity anomaly. An example of similar size to Mt. Toondina is the Connolly' Basin structure in Western Australia *[Shoemaker et al.,* 1989; *Shoemaker and Shoemaker, 1989].* Connolly Basin is a 9-km-diameter impact structure characterized by a 2 mGal gravity high over the central uplift due to the presence of relatively high-density rocks. Although vastly larger, the Manicouagan impact in Quebec (65 km diameter) shows a similar pattern *[Sweeney,* 1978]. Manicouagan has a central gravity high due to relative high-density rocks surrounded by an annular low; total gravity relief is ~ 8 mGal. However, a pattern of a central gravity high is not always the case; at the Steinheim Basin the central uplift is characterized by a negative gravity anomaly [*Pilkington and Grieve, 19921.*

SEISMIC REFLECTJON DATA

Unraveling details of the structure at Mt. Toondina has been greatly facilitated by two seismic reflection lines which cross the feature. One of the lines (85 YQZ) trends nearly east-west (Figure 5) and passes directly across the central uplift; the second line (85 XQF, not shown) trends northeast and passes obliquely across the structure. Record sections for these lines were kindly provided by the South Australian Department' Mines and Energy.

The east-west line record section (Figure 5) shows a series of prominent reflectors at depths of 0.2, 0.6, 0.8 - 0.9, and >1 sec two-way travel time (TWTT). These reflectors can be traced across much of the Arckaringa Basin and can be tied to specific stratigraphic units observed in the Cootanoorina well located 7 km southwest of Mt. Toondina [*Wopfner*, 1970; *Hibburt*, 1984]. Reflectors in the Cadna-owie Formation, the Algebuckina Sandstone, the Mt. Toondina Formation, and the underlying Stuart Range Formation of Permian age can be traced in the seismic record section from the Cootanoorina well to Mt. Toondina. The "V" shaped gore in the reflection section extending between stations 540 to 585 is a gap in the vibration points.

Outside of the Mt. Toondina structure, at stations <460 and >660, the reflectors at depths less than 1.0 sec TWTT are continuous and essentially flat lying. Near the center of Mt. Toondina (station 560) the reflectors at shallow levels, corresponding to the Bulldog Shale, Cadna-owie Formation, Algebuckina Sandstone, and Mt. Toondina Formation, all steepen and become shallower toward the center. These reflectors can be extrapolated to the surface where they correlate with the same units in outcrop with which they are correlated in the well data. Surrounding the uplift (near stations 510 and 600) is a zone where the reflectors are depressed below their regional level.

Surrounding the uplift, at stations 490 and 640, the strata have dropped downward and inward. These displacements have been accommodated in part by a series of inward dipping normal faults. This downward and inward motion resulted in the formation of a ring structural depression surrounding the central uplift. The seismic reflection data indicate that the strata above the base of the Stuart Range Formation have been pushed up into the central uplift at Mt. Toondina.

At depths > -0.6 sec TWTT the reflectors assigned to the Adelaidean stratigraphic section are essentially continuous beneath the structure. There is a hint of slight disruption of strata at this depth, although the disruption may be an artifact resulting from velocity effects within the overlying disturbed zone. All of the deformation occurs above the base of the Stuart Range Formation; strata at deeper levels are essentially undisturbed, as indicated by the continuity of the reflectors. Thus, the strong deformation affects only units of Permian and younger age.

The northeast-trending seismic reflection line, which trends obliquely across the edge of the structure, shows a shallow depression where it crossed within the crater ring structural depression. This same depression is observed in the east-west profile at stations 510 and 600. The units in the northeast trending line are observed to be depressed -0.04 - 0.06 sec TWTT relative to their surrounding level.

GRAVITY MODELING

Density Determinations

In an effort to constrain gravity models of the Mt. Toondina structure, hand specimens of the local geologic units were collected for density analysis. Samples of the Mt. Toondina Formation were collected from the section described by *Freytag [1965]* and elsewhere in the central uplift. Cadna-owie Formation samples were obtained from a spoil pile on the flank of the central uplift. The Algebuckina Sandstone samples were collected *from* outcrop around the central uplift and samples of the Bulldog Shale were collected south of and along the east flank of the uplift, Most samples are somewhat weathered.

Figure 6 illustrates the density determination for each of the rock types sampled. Several determinations were made for each type, from both multiple samples and subsamples from single specimens. Error bars in Figure 6 illustrate the variation in the calculated density; the predominate source of uncertainty in the density value is the sample volume. Densities were measured on dry samples; wet densities would be significantly higher, particularly for sandstones.

Average densities for rock exposed at Mt. Toondina range from 1.6 *to* 2.9 g cm^{-3}; most samples range from 1.8 to 2.0 g cm^{-3}, The Cadna-owie Formation sandstones and the Algebuckina Sandstone have the highest densities (1.9 - 2.9 g cm^{-3}), but these are relative thin units. (Combined thickness of both formations at Mt. Toondina is -75 m.) Densities for Mt. Toondina Formation rocks range from 1.6 g cm^{-3} for carbonaceous claystones to 2.0 g cm^{-3} for clayey sandstones. As the Mt. Toondina Formation is characterized by siltstone with minor sandstone, the formation density is probably in the range of 1.9 - 2.0 g cm^{-3}. Water saturation, as would occur *in situ*, would increase the densities as much as 10 - 20% above the dry densities presented here. Seismic refraction data for the region [*Moorcroft*, 1964] indicates velocities of 2.59 km see-l for shallow units and 5.2 to 5.7 km See-l below 600 m corresponding to densities of 2.2 to 2.7 g cm^{-3}. Therefore, on the basis of the measured dry densities, the *in situ* geologic conditions (water saturation), and the velocity data, the mean densities of these formations are considered to be greater than the measured values for dry surface samples.

Our density data are consistent with those reported by *Milton and Morony [1976]* who cite average densities of ~2.07 g cm^{-3} for the Permian and Mesozoic sediments of the Arckaringa Basin and 2.65 g cm^{-3} for crystalline basement rocks. Not all sediments within the basin are, however, of such low density. Dolomites from the Wintinna and Boorthanna Troughs have densities of 2.64 to 2.85 g cm^{-3}, Ordovician (?) quartzites from the Boorthanna Trough have densities of 2.69 g cm^{-3}, and some Permian and Mesozoic sedimentary rock have densities of 2.25 g cm^{-3}.

Modeling

In order to better understand the origin of the gravity anomalies and their implications for crustal structure, we modeled the residual gravity anomaly using a 2 1/2 D gravity modeling program. Constraints on the "gravity model are provided by the exposed geology; two seismic reflection profiles which cross the structure; strati graphic control from outcrop and from seismic correlation with the stratigraphic control at the Cootanoorina well; and density determinations. The local Permian and Mesozoic stratigraphy consists of about 260 m of Stuart Range Formation, 330 m of Mt. Toondina Formation, 10 - 40 m of Algebuckina Sandstone, 30 m of Cadna-owie Formation, and 100 m of Bulldog Shale [*Wopfner*, 1970; *Allchurch et al., 1973; Hibburt, 1984]*. The Permian strata rest unconformably on beds of possible Devonian age which are, in turn, underlain by a thick sequence of late Precambrian and Cambrian strata (Adelaidean).

The gravity model of the Mt. Toondina structure (Figure 7) includes three layers: (1) the lowest layer represents the Mt. Toondina Formation and has a thickness of 330 m and a density of 2.10 g cm^{-3}; (2) the middle layer is 75 m thick, has a density of 2.12 g cm^{-3}, and corresponds to the older Mesozoic units (Algebuckina Sandstone and Cadna-owie Formation); and (3) the uppermost layer is 100 m thick and has a density of 1.90 g cm^{-3} and corresponds to the Bulldog Shale. Observed residual and calculated gravity are fairly well matched in a model in which the Mesozoic units and Mt. Toondina Formation are brought to the surface in the central uplift and the upper two units are depressed by -90 m in an annular zone slightly more than ·1 km wide surrounding the central uplift. The densities used in the model are probably consistent with the *in situ* densities.

The result of high density units being brought to the surface in the central uplift, in relation to the surrounding lower density Bulldog Shale, results in a central gravity high surrounded by an annular low. The gravity model further indicates that the Mt. Toondina structure at its particular level of exposure has a diameter of -4 km, that the structural relief within the ‘central uplift exceeds 200 m, and that the region around the central uplift has been depressed by -90 m relative to its normal stratigraphic depth.

The gravity model is non unique in that many combinations of densities and model body dimensions can reproduce the observed anomalies. However, the model is consistent with the observed geology at the surface, the seismic reflection data, sample densities, and structure expected for an impact crater. Although the annular low is modeled as being the result of down warping of the Bulldog Shale as suggested by the depressed reflectors in the seismic profile, part of the mass deficit might result from the presence of brecciation or fracturing of the rocks.

DISCUSSION

The suggestion of previous investigators [*Freytag*, 1964, 1965; *Wopfner*, 1977; *Jones*, 1988] that the Mt. Toondina structure is a salt dome was based chiefly on the diapir-like relation of the rocks of the central uplift to the beds of the surrounding region and the discovery of salt domes elsewhere in the Arckaringa Basin. However, a salt dome model is not consistent with the observed data: (1) salt does not occur in the Mt. Toondina area in Permian and younger units; although salt does occur in the late Proterozoic Adelaidean rocks [*Sani*, 1986] in the region and salt domes are present (e.g., 80 km northwest of Mt. Toondina); and (2) the structural deformation at Mt. Toondina is limited to Permian and younger units. Deformation of "the exposed beds of the central uplift at Mt. Toondina involves circumferential shortening and uplift; beds that overlie salt diapirs tend to exhibit extensional rather than compressional deformation. Additionally, the elastic rocks of Permian to Cretaceous age are the ones so deformed, not the older salt. The central uplifts of impact structures do resemble diapirs. However, such uplifts are driven not by bouancy as in a salt dome, but by the prompt collapse of the transient cavity walls and flow of the displaced material toward the center of the crater. As at Mt. Toondina, these uplifts are commonly marked by positive gravity anomalies.

The Mt. Toondina structure can be most closely compared with the Middle Miocene Steinheim Basin in Germany [*Reiff*, 1977] and the partly buried Flynn Creek, Tennessee crater of Late Devonian age [*Roddy*, 1977]. Both impact structures are formed in nearly flat-lying sedimentary rocks and are -3.5 km in diameter, similar to the size of the Mt. Toondina. Both are partly filled craters with pronounced diapir-like central uplifts that underlie the central topographic peak. Surrounding the central peaks are relatively flat floors which are underlain by fairly shallow structural depressions.

In Australia, the closest known structural analog to Mt. Toondina is the Connolly Basin of Cretaceus age [Shoemaker *and Shoemaker,* 1989]. The Connolly Basin is an exhumed crater -9 km in diameter with a relatively small central uplift. Connolly is also underlain by Precambrian salt deposits and is close to known salt diapirs [We *lls*, 1980]. A seismic profile across the center of the Connolly structure reveals that the salt is essentially undisturbed at depth beneath the feature. The central uplift is surrounded by a structural moat bounded by normal faults, the deformation is confined to the relatively shallow units. A positive residual gravity anomaly is localized over the central uplift; it is surrounded by a sequence of subdued gravity highs and lows *[Shoemaker et al., 1989].*

Seismic reflection profiles revealing broad structural features somewhat similar to those at Mt. Toondina have been obtained for many impact structures around the world including the Red Wing Creek structure in North Dakota [*Brenan*, 1975]; the Haughton impact structure in arctic Canada [*Hajnal et al.*, 1988: *Scott and Hajnal, 1988];* the Siljan impact structure in Sweden [*Juhlin and Pedersen, 1987];* the Tookoonooka structure in the Eromanga Basin of Australia [*Gorter et al.*, 1988] and the Mjolnir structure, a possible impact structure in the Barents Sea [*Gudlaugsson, 1993].*

The structural relief of the central uplift at Mt. Toondina is consistent with data for other complex impact craters, *Grieve et al.* [1981] present a relation between average structural uplift (SU) and crater diameter (D) ($SU = 0.06D^{1.1}$). This relation would indicate a structural uplift of about 280 m for a diameter of 4 km. When account is taken of the effects of erosion and the upward displacement within the Mt. Toondina Formation that is not recognizable in the gravity model, the observed relief at Mt. Toondina is consistent with average expectations.

SUMMARY

The gravity data combined with the seismic reflection data and surface structural geologic mapping for the Mt. Toondina structure *in* South Australia, reveal that the central uplift is surrounded by a ring structural depression. Detailed geologic mapping indicates that the Permian, Jurassic (?), and lower

Cretaceus beds of the central uplift have all been deformed in convergent centripetal flow. Further, the seismic reflection data show that deformation dies out with depth. Below -800 m, the reflectors pass beneath the structure undisturbed indicating little or no deformation below this depth.

The Mt. Toondina impact structure is defined by a simple residual gravity anomaly. Relative to the adjacent terrane, the central uplift is marked by a positive anomaly of +1 mGal, 1.2 km in diameter, surrounded by an annular gravity low (-0.5 mGal) having a width of -1 km. The overall diameter of the feature is --4 km, Gravity modeling suggests that relatively high density units (Algebuckina Sandstone, Cadna-owie Formation, and Mt. Toondina Formation) have been raised up into the central uplift in excess of 200 m and that the surrounding Bulldog Shale fills a ring structural depression within the crater interior that is -90 m deep

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FIGURE CAPTIONS

Fig. 1. Map showing location of Mt. Toondina structure in South Australia.

Fig. 2. Oblique aerial view to the west of the Mt. Toondina structure showing the central uplift and surrounded by gently sloping surficial deposits, The dark ring is formed by trees and brush concentrated along the Algebuckina Sandstone aquifer; a wavy line of trees following the Algebuckina outcrop reflects steeply plunging folds. The bright material in the center is salt crusted outcrop of the Mt. Toondina beds. The bright line extending across the feature from top to bottom is a road along which the seismic reflection line (85 YQZ) was acquired; other roads are also evident. (Photo courtesy David Roddy, U. S. G. S.)

Fig, 3a. Bouguer gravity map of the region; contour interval is 0.5 mGal. Station locations are indicated by crosses. Data include points within an 8 km x 8 km square centered on the uplift. Fig. 3b. Oblique 3D perspective view of the Bouguer gravity field seen from the southeast.

Fig. 4a. Residual Bouguer gravity field. Third - order polynomial surface has been removed to generate the residuals. Contour interval is 0.1 mGal. Shaded area has gravity < - 0.1 mGal. Fig. 4b. Oblique 3D perspective view of the residual gravity field seen from the southeast. The central high and surrounding low are easily seen from this perspective. Fig. 4c, 3rd order polynomial field removed from Bouguer gravity; contour interval 1.0 mGal. Fig. 4d. Oblique 3D perspective view of the third order polynomial surface seen from the southeast.

Fig, 5. East-west seismic reflection profile (Line 85 YQZ) across the center of the structure. Upper panel shows the original reflection record; lower panel illustrates our interpretation of the structure. Residual Bouguer gravity values are plotted above the interpreted profile, B: Bulldog Shale; Mz: Mesozoic units (Cadna-owie Formation and Algebuckina Sandstone).

Fig. 6. Density determinations for samples collected at Mt. Toondina. Measurements have been averaged by rock type. Variations in the calculated

densities among samples are indicated by error bars. SS: Sandstone; CLAY: Claystone.

Fig. 7. Two and a half dimensional gravity model showing the proposed structure. Horizontally stripped unit is the Bulldog Shale (p = 1.90 g cm^{-3}); stippled unit represents the Algebuckina Sandstone and the Cadna-owie Formation (p = 2.10 g cm-3); the under] ying white unit is the Mt. Toondina Formation (p = 2.12 g cm^{-3}). Circles in the upper panel indicate residual gravity, the solid line is model gravity. Vertical exaggeration is 10:1 in the model cross section. Scale is in meters.

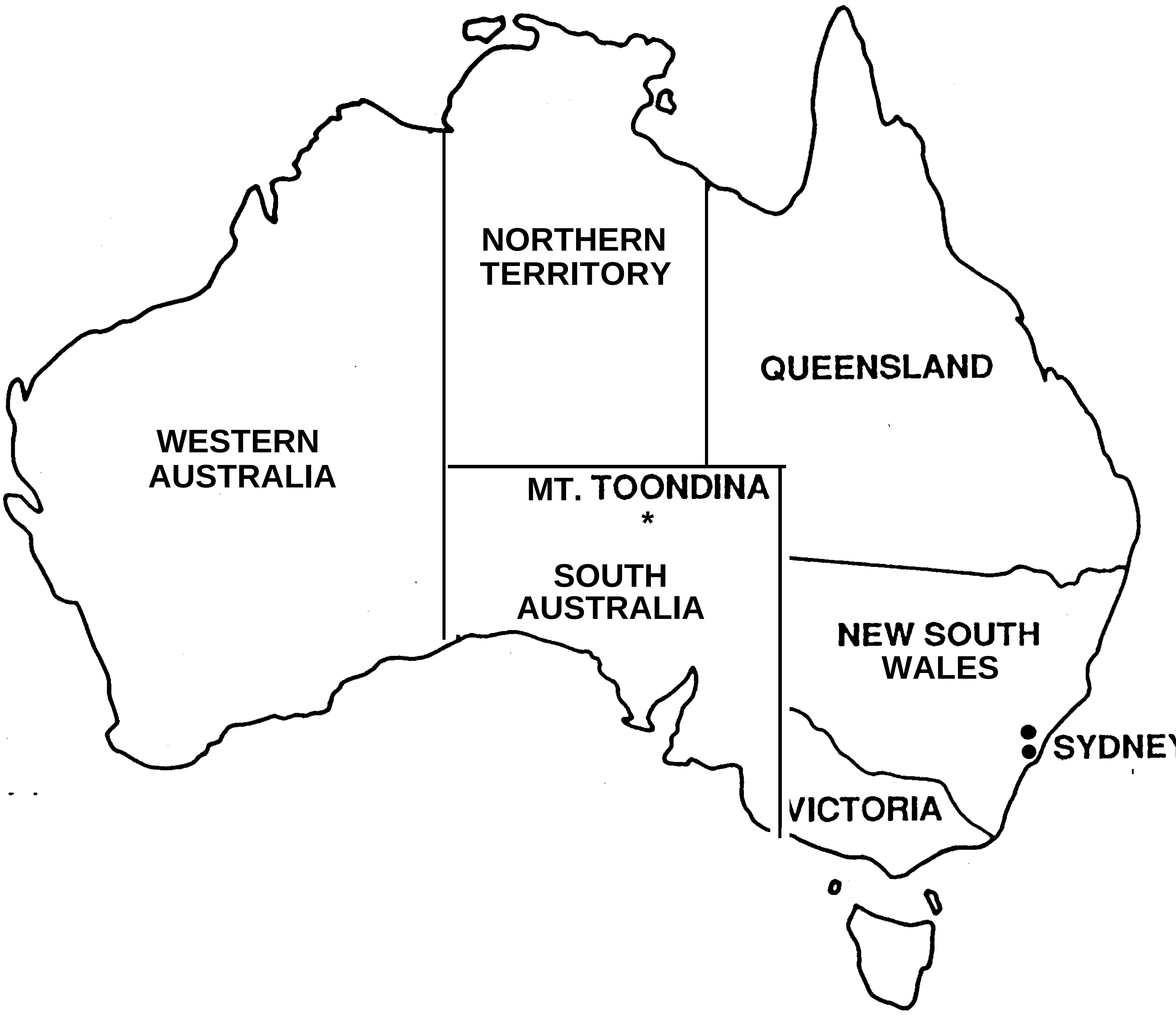

NORTHERN
TERRITORY
QUEENSLAND
WESTERN
AUSTRALIA
MT. TOONDINA
*
SOUTH
AUSTRALIA
NEW SOUTH
WALES
SYDNEY
VICTORIA

FIGURE 1.

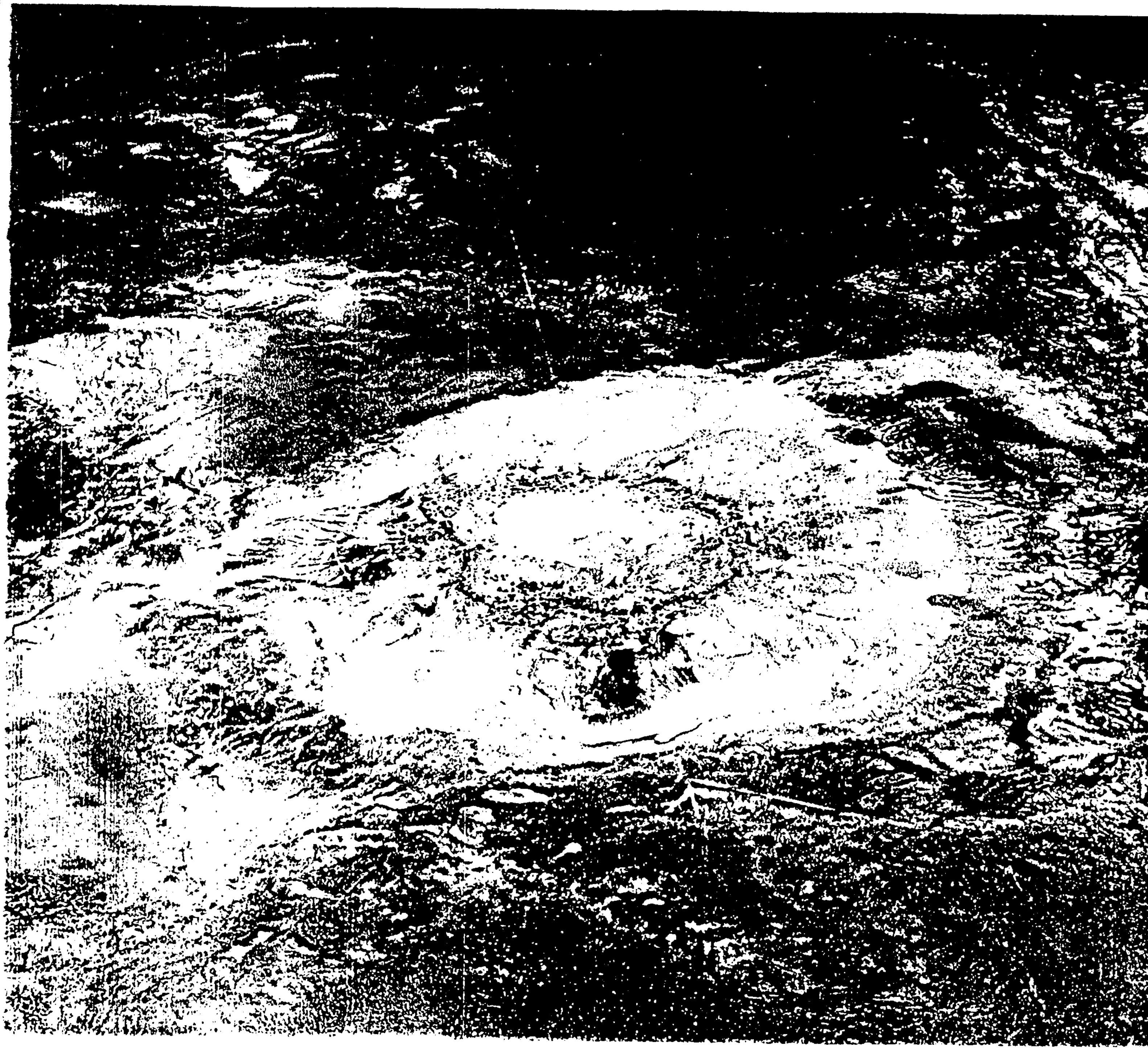


FIGURE 2.

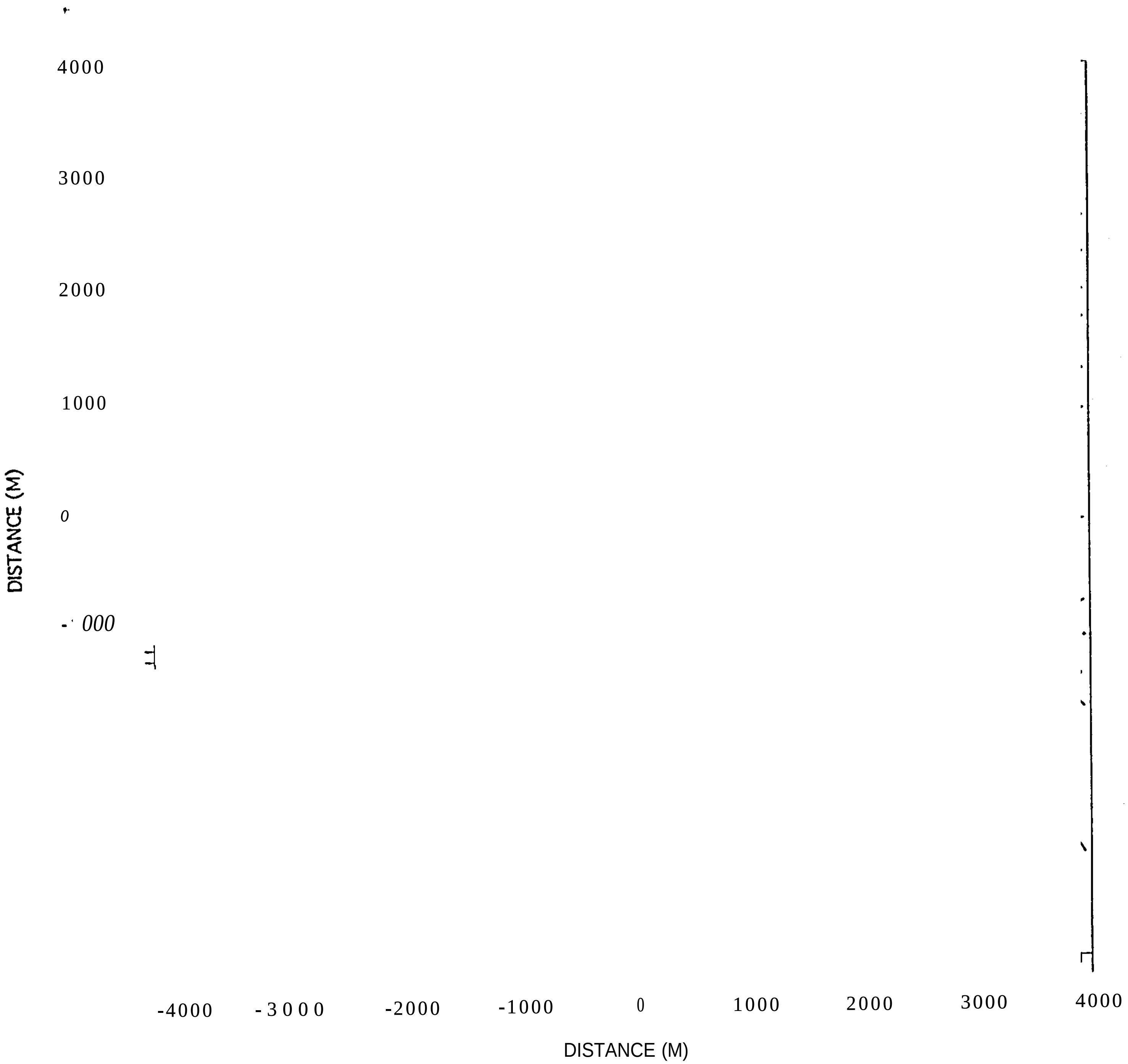

4000
3000
2000
1000
0
DISTANCE (M)
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
DISTANCE (M)

FIGURE 3A.

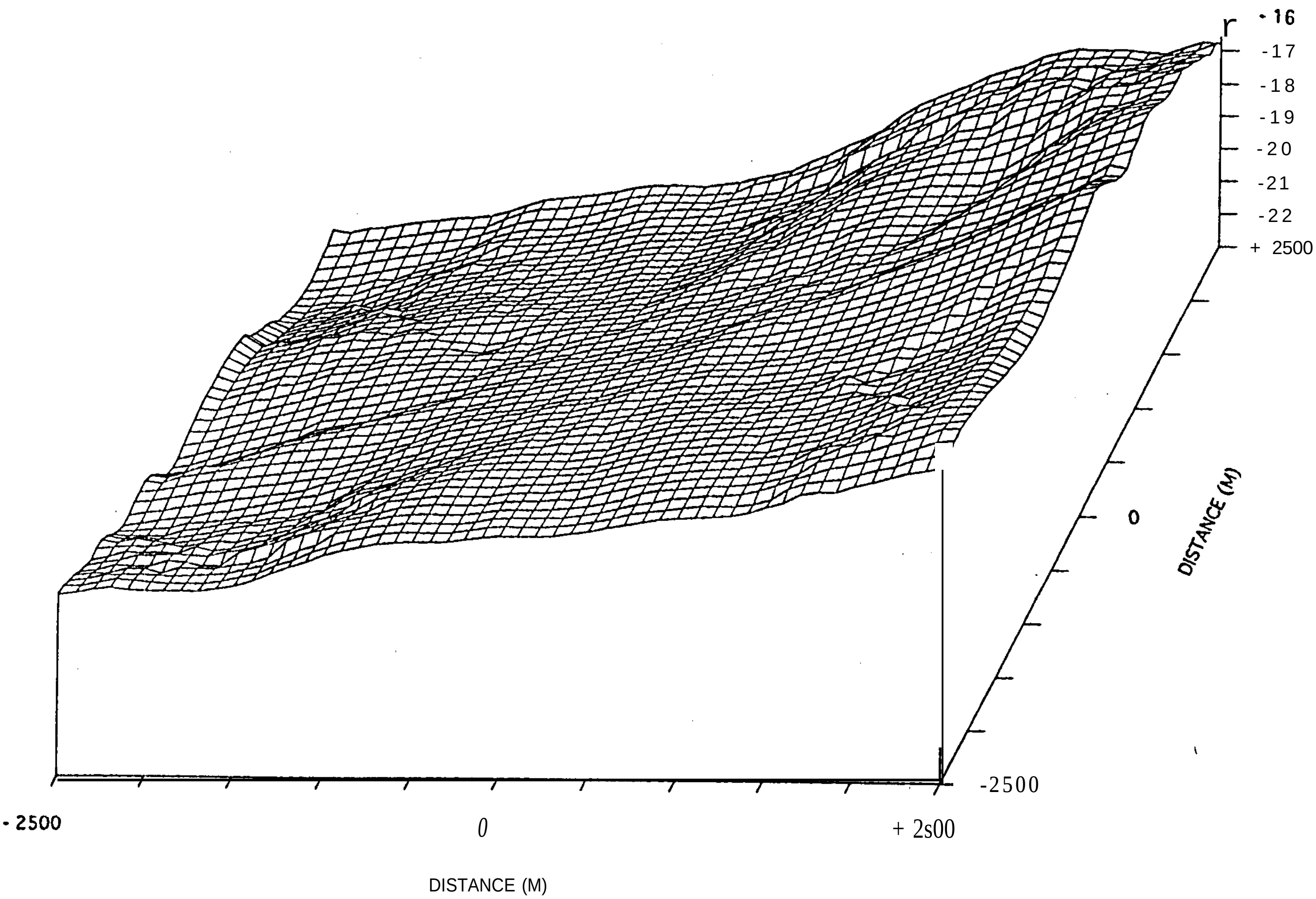
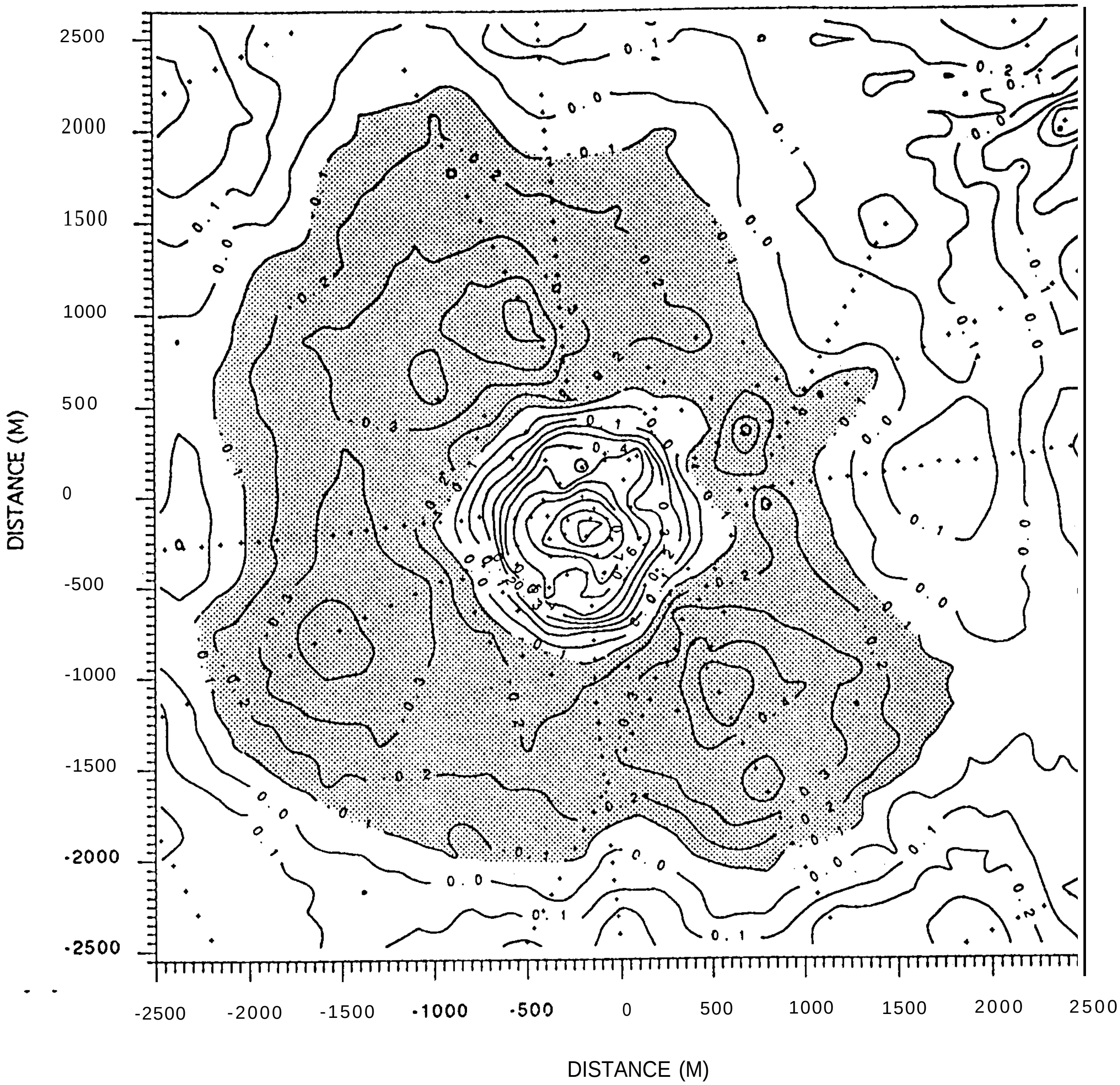
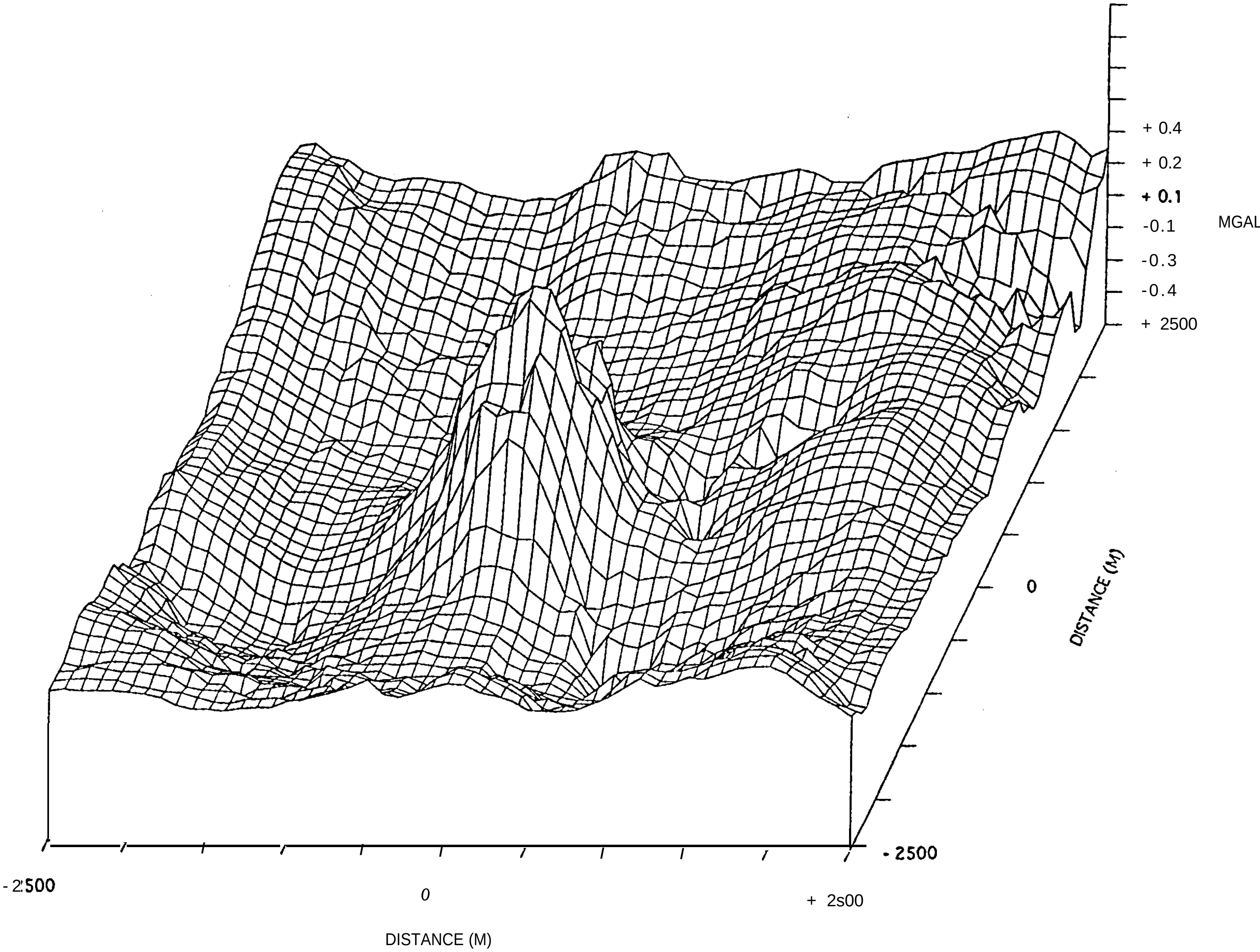

- 16
-17
-18
-19
-20
-21
-22
+ 2500
0
DISTANCE (M)
-2500
- 2500
0
+ 2s00
DISTANCE (M)

FIGURE 3B.



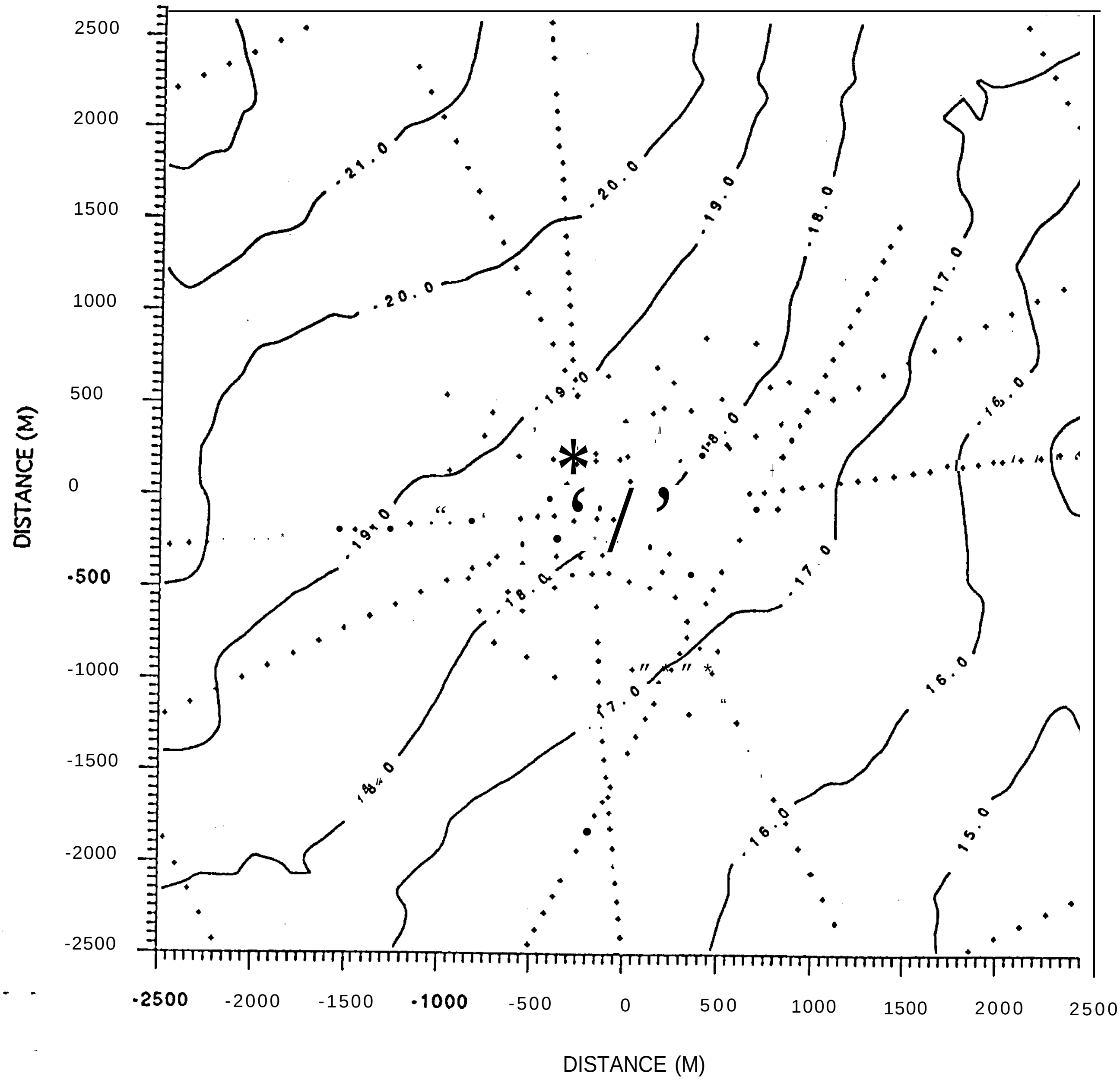
DISTANCE (M)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
2000
2500
DISTANCE (M)

FIGURE 4A.



+ 0.4
+ 0.2
+ 0.1
-0.1
MGAL
-0.3
-0.4
+ 2500
0
DISTANCE (M)
- 2500
- 2500
0
+ 2s00
DISTANCE (M)

FIGURE 4B.



DISTANCE (M)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
2000
2500
DISTANCE (M)
21.0
20.0
20.0
19.0
19.0
19.0
18.0
18.0
18.0
18.0
17.0
17.0
17.0
16.0
16.0
16.0
15.0

FIGURE 4C.

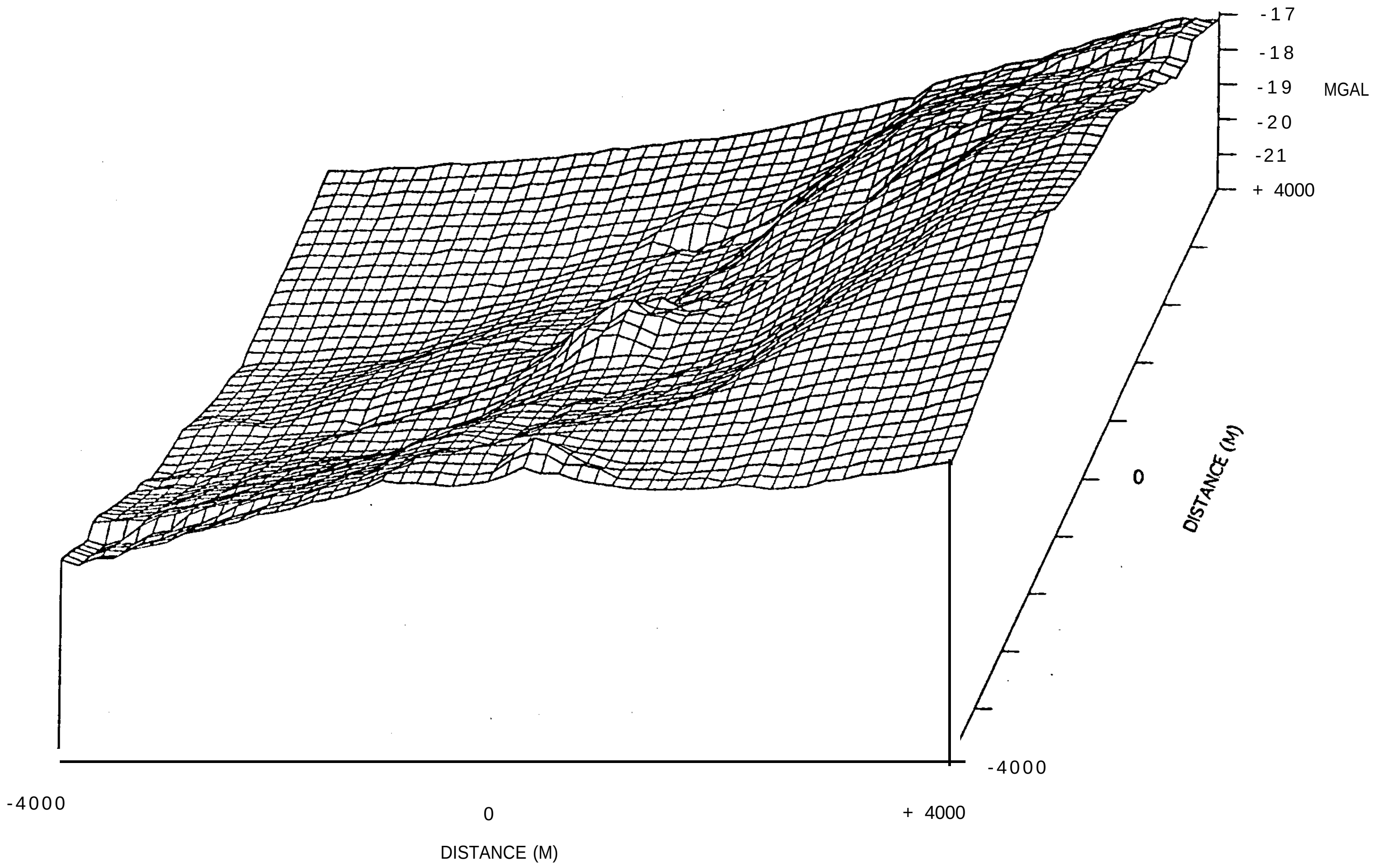

-17
-18
-19
MGAL
-20
-21
+ 4000
0
DISTANCE (M)
-4000
-4000
0
+ 4000
DISTANCE (M)

FIGURE 4D.

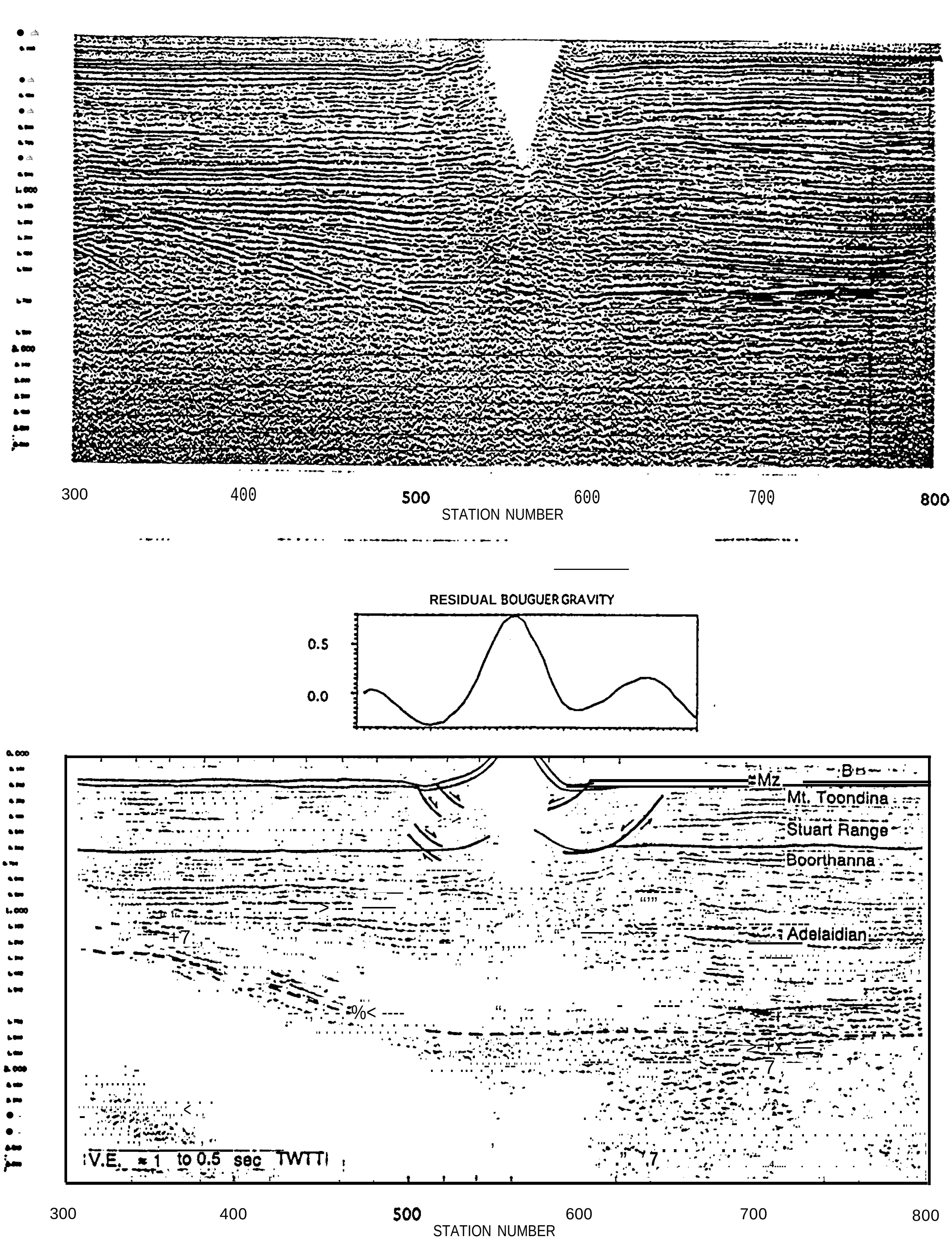

300
400
500
600
700
800
STATION NUMBER
RESIDUAL BOUGUER GRAVITY
0.5
0.0
Mz
Mt. Toondina
Stuart Range
Boorthanna
Adelaidian
V.E. ≈ 1 to 0.5 sec TWTT
300
400
500
600
700
800
STATION NUMBER

FIGURE 5.

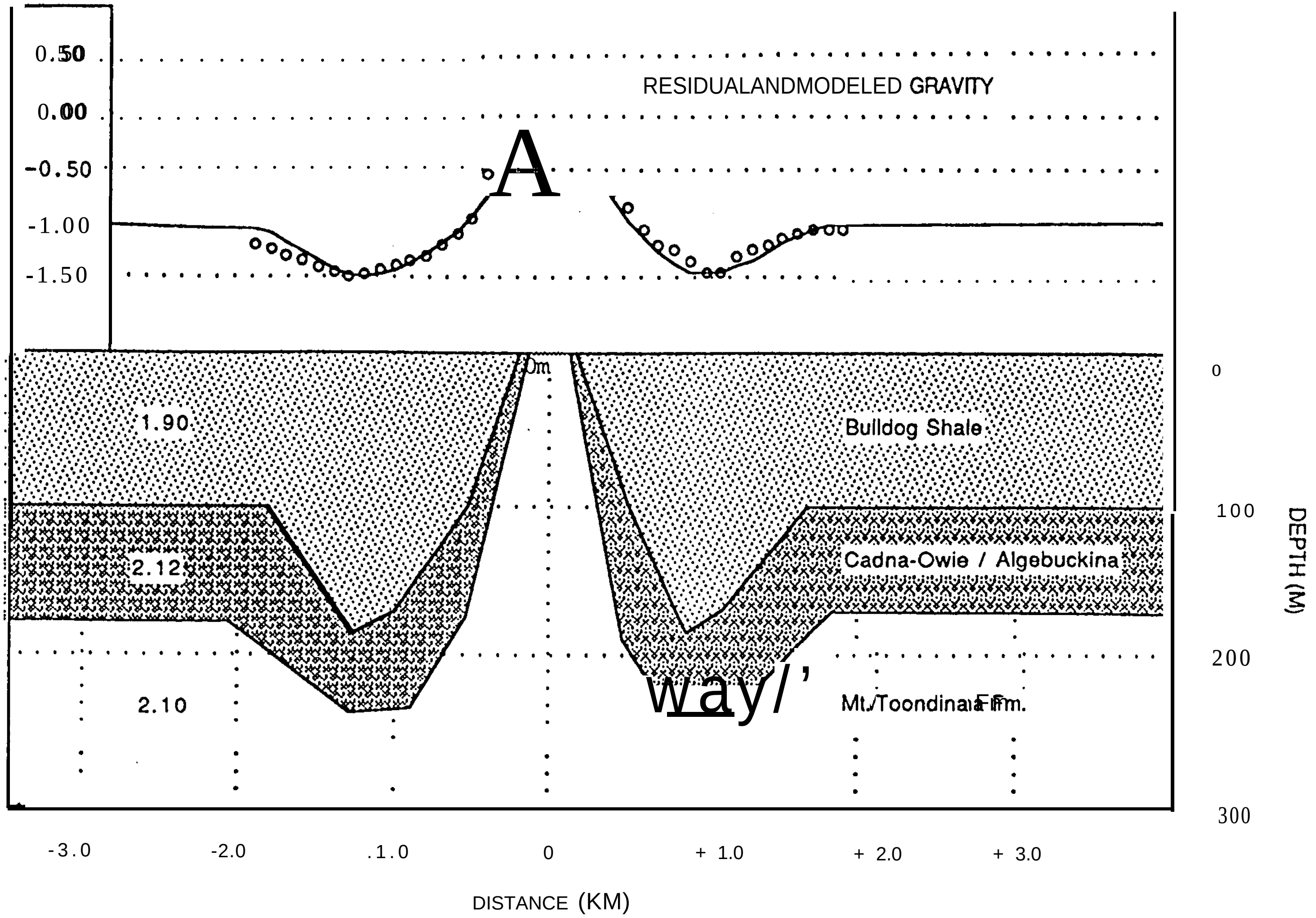
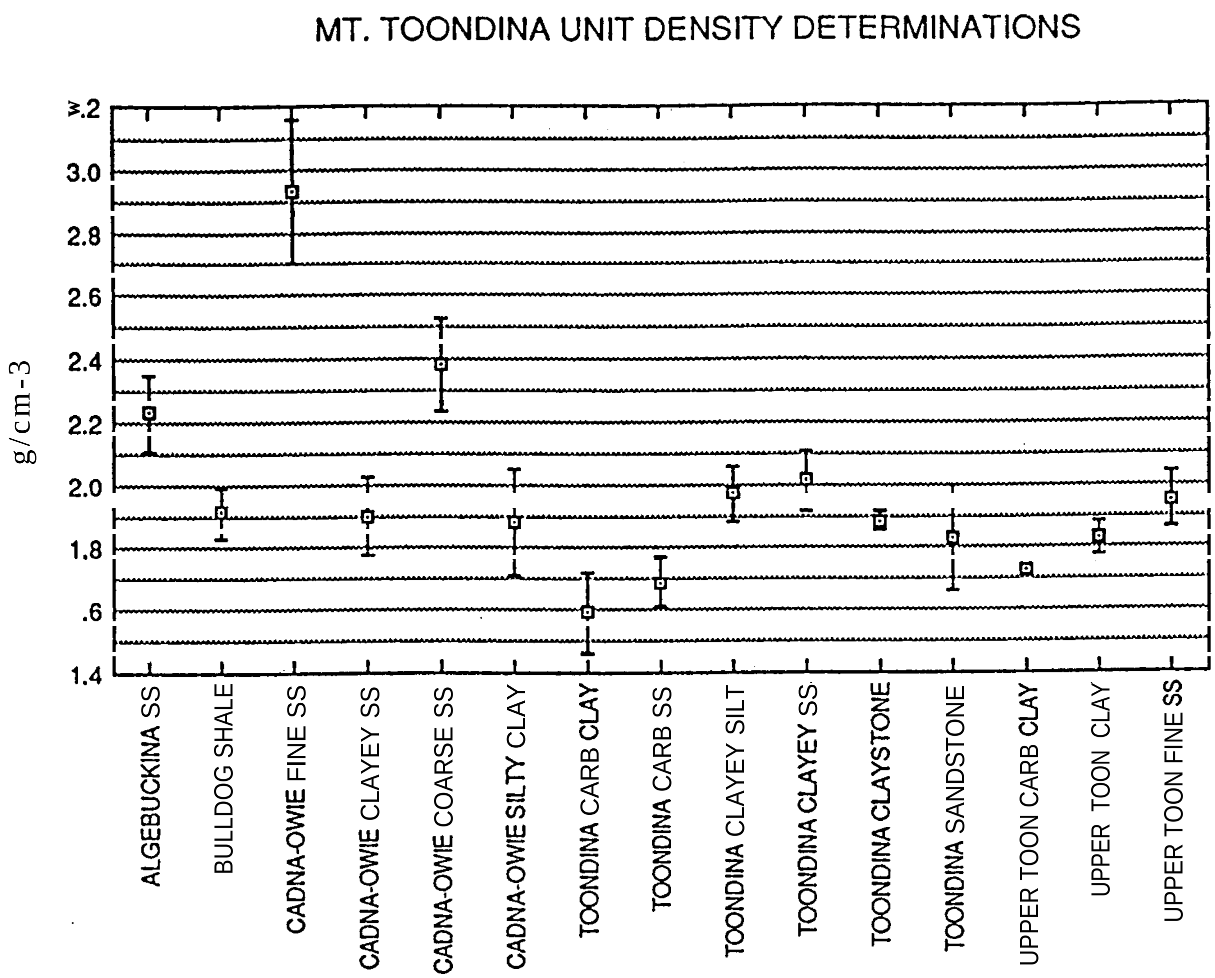

RESIDUALANDMODELED GRAVITY
0.50
0.00
-0.50
-1.00
-1.50
A
1.90
2.12
2.10
Bulldog Shale
Cadna-Owie / Algebuckina
Mt.Toondina Fm.
0
100
200
300
DEPTH (M)
-3.0
-2.0
.1.0
0
+ 1.0
+ 2.0
+ 3.0
DISTANCE (KM)

FIGURE 6.



MT. TOONDINA UNIT DENSITY DETERMINATIONS
g/cm-3
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
.6
1.4
ALGEBUCKINA SS
BULLDOG SHALE
CADNA-OWIE FINE SS
CADNA-OWIE CLAYEY SS
CADNA-OWIE COARSE SS
CADNA-OWIE SILTY CLAY
TOONDINA CARB CLAY
TOONDINA CARB SS
TOONDINA CLAYEY SILT
TOONDINA CLAYEY SS
TOONDINA CLAYSTONE
TOONDINA SANDSTONE
UPPER TOON CARB CLAY
UPPER TOON CLAY
UPPER TOON FINE SS

FIGURE 7.